

PRINTED CIRCUIT LINEAR MOTOR
BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates to linear motors and, more particularly, to armatures of linear motors.

2. Background Art

[0002] A typical linear motor essentially includes N coils or N sets of coils fixedly positioned adjacent each other and a plurality of alternating north and south magnetic poles positioned in spaced parallel relation to the coils. The coils and the plurality of magnetic poles are movable with respect to each other in response to each of the N coils or the N sets of coils receiving selective excitation from an N phase source of electrical power.

[0003] In the prior art, each coil of a linear motor is formed from a continuous conductor wound into a suitable form. The cross-sectional area of the conductors utilized to form each coil of a linear motor is selected based on the force the linear motor is designed to generate. Thus, a linear motor designed to produce a greater force will typically have coils wound from wire having a larger cross-sectional area, while a linear motor designed to produce a lesser force has coils wound from wire having a smaller cross-sectional area. It is to be appreciated, however, that the number of turns of coils multiplied by the current flowing therethrough determines the force generated by each coil of a linear motor. Generally speaking, however, wires having a larger cross-sectional area are utilized to form coils of linear motors designed to produce greater force and wires having smaller cross-sectional areas are utilized to form coils of linear motors designed to produce lesser force.

[0004] There is a growing need for linear motors of reduced size for assembly of electronic components to electronic assemblies and for mating of fiber optic assemblies. A problem with producing a smaller linear motor, however, is that the desired cross-sectional area of wire utilized to form the coils of these linear motors is smaller than the smallest cross-sectional area of wire conventional state-of-the-art coil winding machines are designed to process. Thus, as the cross-sectional area of the wire utilized to form coils of a linear motor decreases, the difficulty in winding such wire into coils for linear motors increases. This difficulty arises from the physical limitations of coil winding machines to effectively manipulate wires having smaller cross-sectional areas suitable for use in smaller linear motors. Accordingly, there is a need to produce smaller linear motors of reduced size having coils formed from one or more conductors, each conductor having a smaller cross-sectional area than the smallest cross-

09877644-060801

sectional area of a wire capable of being wound into a linear motor coil by a conventional coil winding machine.

[0005] It is, therefore, an object of the present invention to overcome the above problem and others by providing a linear motor having coils formed from one or more conductors having a cross-sectional area smaller than the smallest cross-sectional area of wire capable of being wound effectively with conventional coil winding equipment. It is an object of the present invention to provide linear motor coils formed utilizing a photolithographic process. Still other objects of the present invention will become apparent to those of ordinary skill in the art upon reading and understanding the following detailed description.

SUMMARY OF THE INVENTION

[0006] Accordingly, we have invented a linear motor comprising a magnet track and a magnet assembly coupled to the magnet track. The magnet assembly has a plurality of side-by-side alternating magnetic north poles and magnetic south poles. The linear motor also includes an armature having a plurality of side-by-side electrically conductive coils formed on an electrically and magnetically nonconductive substrate, preferably a printed circuit board (PCB), which is movably coupled to the magnet track such that the side-by-side electrically conductive coils are positioned and movable in spaced parallel relation to the side-by-side alternating magnetic poles. The substrate includes a plurality of electrically nonconductive layers laminated together. Each layer has a plurality of electrically conductive windings formed thereon in side-by-side relation on at least one surface thereof with adjacent conductive windings of each layer electrically isolated from each other on the layer. Each electrically conductive winding of each layer is positioned in registration and electrically connected with a corresponding electrically conductive winding on each other layer to form one of the electrically conductive coils.

[0007] For each coil, the electrically conductive windings on adjacent layers are configured so that magnetic fields produced thereby in response to an electric current flowing through each electrically conductive winding are additive.

[0008] The electrically conductive windings of adjacent layers forming one of the electrically conductive coils are connected in series (i) on or adjacent the centers of the electrically conductive windings or (ii) adjacent the perimeters of the electrically conductive windings. The electrical current flows around the central axis of one of the electrically

conductive windings of adjacent layers from a perimeter thereof toward the central axis and flows around the central axis of the other of the electrically conductive windings of adjacent layers from on or adjacent the central axis toward the perimeter thereof.

[0009] Preferably, each layer includes a plurality of heat transfer vias therethrough. The plurality of heat transfer vias of each layer is positioned in registration with the corresponding plurality of heat transfer vias in the other layers. The windings of each coil positioned in registration are electrically connected via a conductor received in at least one hole and/or via formed in each layer. A plurality of spacers can be positioned between two or more adjacent layers for maintaining the two or more adjacent layers in spaced parallel relation with a gap therebetween. Each layer can be rigid or flexible and the magnet assembly can include at least one magnet coupled to the magnet track. The plurality of side-by-side electrically conductive coils can include an integer multiple of N coils, with every Nth coil electrically connected together.

[0010] In operation, selectively energizing adjacent conductive coils with different phases of an N phase electrical source causes the armature to move relative to the magnet assembly.

[0011] We have also invented a linear motor comprising a linear armature having a plurality of layers. Each layer has a plurality of electrically conductive windings formed thereon in side-by-side relation on one surface thereof. The plurality of layers is laminated together with a plurality of electrically conductive windings of each layer positioned in registration. Each electrically conductive winding on each layer is electrically connected with corresponding electrically conductive windings positioned in registration therewith on the other layers, and adjacent electrically conductive windings on each layer are electrically isolated from each other on the layer.

[0012] Electrically conductive windings in registration on adjacent layers are configured to produce magnetic fields that are additive in response to each of the electrically conductive windings in registration receiving an electrical current therethrough.

[0013] The electrically conductive windings in registration on adjacent layers have a common central axis. Around the central axis of each pair of electrically conductive windings in registration on adjacent layers, electric current flows in one of the pair of electrically conductive windings from a perimeter to the central axis thereof, and electrical current flows in the other of the pair of electrically conductive windings from the central axis toward a perimeter

thereof. Two or more electrically conductive windings of each layer can be electrically connected.

[0014] Lastly, we have invented a motor comprising an armature having a plurality of side-by-side electrically conductive coils formed on an electrically and magnetically nonconductive substrate with adjacent coils electrically isolated from each other. Each coil includes a plurality of electrically conductive windings positioned coaxially and electrically connected so that in response to an electrical current flowing therethrough, each winding produces a magnetic field having the same polarity.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] Fig. 1 is perspective view of a linear motor having an armature with a substrate formed in accordance with the present invention;

[0016] Fig. 2 is a partially exploded end view of the substrate taken along line II-II shown in Fig. 1;

[0017] Fig. 3a is a view of the patterned surface of one of the layers forming the substrate taken along line IIIa-IIIa in Fig. 2;

[0018] Fig. 3b is a view of the patterned surface of one of the layers forming the substrate taken along lines IIIb-IIIb in Fig. 2;

[0019] Fig. 4a is a view of the patterned surface of one of the layers forming the substrate taken along line IVa-IVa in Fig. 2;

[0020] Fig. 4b is a view of the patterned surface of one of the layers forming the substrate taken along line IVb-IVb in Fig. 2;

[0021] Fig. 5a is a view of the patterned surface of one of the layers forming the substrate taken along line Va-Va in Fig. 2; and

[0022] Fig. 5b is a view of the patterned surface of one of the layers forming the substrate taken along line Vb-Vb in Fig. 2.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0023] With reference to Fig. 1, a linear motor 2 includes a stator 4 and a forcer 6. Forcer 6 includes an elongated, preferably rectangular, armature 8 having an elongated upper edge received between legs of a U-shaped cover 10. Preferably, an epoxy (not shown) received

between the legs of U-shaped cover 10 is utilized to secure the elongated upper edge of armature 8 thereto with the legs of U-shaped cover 10 extending partially over opposite surfaces of armature 8.

[0024] Stator 4 includes a U-shaped magnet track 12 having a pair of upwardly extending legs which have a pair of opposing surfaces 14a and 14b which define a gap 16 between the legs of U-shaped magnet track 12. A magnet assembly 20 is received in gap 16 and is secured to surface 14a. The side of magnet assembly 20 opposite surface 14a has a plurality of side-by-side alternating magnetic north poles 22 and magnetic south poles 24. Magnet assembly 20 can be formed from a plurality of bar magnets 28 positioned side-by-side along the length of gap 16 or from a single elongated magnet (not shown) having magnetic north poles 22 and magnetic south poles 24 formed therein.

[0025] Another magnet assembly 20 can be secured to surface 14b across gap 16 from magnet assembly 20 secured to surface 14a. Preferably, the magnetic poles 22 and 24 of the magnet assembly 20 secured to face 14b are the magnetic complement of magnetic poles 22 and 24 of magnet assembly 20 secured to surface 14a. Thus, across gap 16, each magnetic north pole 22 of magnet assembly 20 secured to surface 14a is in opposition with a magnetic south pole 24 of the magnet assembly 20 secured to surface 14b. Moreover, across gap 16, each magnetic south pole 24 of magnet assembly 20 secured to surface 14a is in opposition with a magnetic north pole 22 of magnet assembly 20 secured to surface 14b. The terminal ends of the legs of U-shaped magnet track 12 includes bearing races 30 to be described hereinafter.

[0026] Armature 8 includes an electrically and magnetically nonconductive substrate 34, preferably a printed circuit board (PCB), having a plurality of electrically conductive coils 36-46 formed thereon in side-by-side relation between a first end 50 and a second end 52 of substrate 34. Preferably, adjacent coils 36-46 are electrically isolated from each other. Adjacent second end 52, substrate 34 includes an array of plated through-holes 54 which extend through substrate 34. A plurality of printed circuit leads 56 formed on substrate 34 electrically connect pairs of plated through-holes 54 to one or more coils 36-46.

[0027] Each plated through hole 54 can be connected to an amplifier 58 via a conductor 60 of a wiring harness 61. Amplifier 58 supplies to coils 36-46 appropriate drive signals which cause currents I to flow through coils 36-46 in a manner known in the art to produce relative motion between forcer 6 and stator 4.

[0028] Substrate 34 preferably includes a plurality of heat transfer vias 62 which extend through substrate 34. These heat transfer vias 62 enable heat generated by armature 8 during operation to flow from the inside of substrate 34 to the surfaces thereof.

[0029] Linear motor 2 includes a Hall-effect sensor 64 preferably connected to U-shaped cover 10 adjacent one end thereof. Hall-effect sensor 64 is electrically connected to amplifier 58 which utilizes the output of Hall-effect sensor 64 to control the application of electrical currents I to coils 36-46 to produce relative motion betweenforcer 6 or stator 4. The terminal ends of the legs of U-shaped cover 10 include bearing races 66.

[0030] When linear motor 2 is assembled, the upper edge of armature 8 is secured between the legs of U-shaped cover 10. Thereafter, armature 8 is received in gap 16 with coils 36-46 in spaced parallel relation to the side-by-side alternating magnetic poles 22 and 24 of the one or more magnet assemblies 20 also received in gap 16.

[0031] To enableforcer 6 to move relative to stator 4, bearings 68 are received between bearing races 30 of U-shaped magnet track 12 and bearing races 66 of U-shaped cover 10 when armature 8 is received in gap 16.

[0032] With reference to Fig. 2, and with ongoing reference to Fig. 1, substrate 34 includes a plurality of electrically nonconductive layers 80₁-80_x laminated together. Each layer 80 can be formed from a rigid material, such as fiberglass, and/or a flexible material, such as a polyimide film. As shown in Figs. 3a-5b, each layer 80 has a plurality of electrically conductive windings photolithographically formed thereon in side-by-side relation on at least one surface thereof. When the plurality of layers 80₁-80_x is laminated together, the plurality of side-by-side electrically conductive windings of each layer 80 is positioned coaxially and in registration. Each electrically conductive winding of each layer 80 is electrically connected with a corresponding electrically conductive winding in registration therewith on the other layers 80 to form one of the electrically conductive coils 36-46.

[0033] Next, exemplary configurations of layers 80 forming an exemplary embodiment of substrate 34 will be described with reference to Figs. 3a-5b, and with ongoing reference to Fig. 2. As shown in Fig. 3a, the patterned surface of layer 80₁ includes a plurality of side-by-side electrically conductive windings 36₁-46₁. Windings 36₁-46₁ correspond to one layer of coils 36-46, respectively. Each of windings 36₁-40₁ and 46₁ of layer 80₁ has one end connected to a unique one of plated through-holes 54. Moreover, windings 42₁ and 44₁ each have one end

thereof electrically connected to a unique one of the plated through-holes 54, but these connections are made via windings 42_x and 44_x formed on the patterned surface of layer 80_x shown in Fig. 5b.

[0034] The winding directions and interconnections of windings 36_1 - 36_x will now be described with reference to a flow of current I_1 . Assuming current I_1 enters winding 36_1 from one of the plated through-holes 54, current I_1 flows in a counterclockwise direction in winding 36_1 , until it exits winding 36_1 and enters winding 36_2 via one of the plated vias 84 adjacent the centers of windings 36_1 and 36_2 . Using the well-known right-hand rule, it can be determined that current I_1 flowing counterclockwise in winding 36_1 produces a magnetic field having a polarization vector which extends outward from the patterned surface of layer 80_1 . The connection of windings 36_1 and 36_2 via one of the plated vias 84 will be described in greater detail hereinafter.

[0035] In the illustrated embodiment, the surfaces of layers 80_1 - 80_2 not shown in Figs. 3a-3b do not include a pattern or any conductive material thereon. These unpatterned surfaces of layers 80_1 and 80_2 are aligned and laminated together with windings 36_1 - 46_1 of layer 80_1 positioned coaxially and in registration with windings 36_2 - 46_2 of layer 80_2 , respectively. In addition, plated through-holes 54 of layer 80_1 are aligned with corresponding mirror image plated through-holes 54 of layer 80_2 ; plated vias 84 and 86 associated with windings 36_1 - 46_1 of layer 80_1 are aligned with corresponding mirror image plated vias 84 and 86 associated with windings 36_2 - 46_2 of layer 80_2 ; and heat transfer vias 62 associated with windings 36_1 - 46_1 of layer 80_1 are aligned with corresponding mirror image heat transfer vias 62 associated with windings 36_2 - 46_2 of layer 80_2 . To form an electrical connection between windings 36_1 - 46_1 of layer 80_1 and windings 36_2 - 46_2 of layer 80_2 , an electrically conductive solder is flowed through the plated vias 84 and 86 of layers 80_1 and 80_2 .

[0036] Current I_1 flows in a clockwise direction in winding 36_2 thereby producing a magnetic field having a polarization vector which extends through and outward from the unpatterned surface of layer 80_2 . With layers 80_1 and 80_2 laminated together to form a pair of layers, as shown in Fig. 2, the polarization vectors of the magnetic fields produced by windings 36_1 and 36_2 in response to current I_1 flowing therethrough are in the same direction. Thus, the magnetic fields produced in response to current I_1 flowing through windings 36_1 and 36_2 are additive.

[0037] With reference to Fig. 4a, and with ongoing reference to Figs. 2-3b, in the illustrated embodiment, the patterned surface of layer 80₂ and the patterned surface of layer 80₃ are laminated together with the plurality of side-by-side windings 36₃-46₃ of layer 80₃ positioned coaxially and in registration with respective windings 36₂-46₂ of layer 80₂. In addition, plated through-holes 54 of layer 80₂ are aligned with corresponding mirror image plated through-holes 54 of layer 80₃; plated vias 84 and 86 associated with windings 36₂-46₂ of layer 80₂ are aligned with corresponding mirror image plated vias 84 and 86 associated with windings 36₃-46₃ of layer 80₃; and heat transfer vias 62 associated with windings 36₂-46₂ of layer 80₂ are aligned with corresponding mirror image heat transfer vias 62 associated with windings 36₃-46₃ of layer 80₃. To avoid shorting between each winding 36₂-46₂ of layer 80₂ and each respective winding 36₃-46₃ of layer 80₃ when layers 80₂ and 80₃ have their respective patterned surfaces laminated together, an insulative coating is deposited on each of the patterned surfaces of layers 80₂ and 80₃. To enable electrical connection between layers 80₁-80_x, the insulative coating in alignment with through-holes 54, plated vias 84 and 86, and heat transfer vias 62 of each layer 80 is removed in a manner known to the art, leaving the insulative coating covering the remainder of the patterned surface of each layer 80. To form an electrical connection between windings 36₂-46₂ on layer 80₂ and respective windings 36₃-46₃ on layer 80₃, solder is flowed through aligned plated vias 84 and 86 of layers 80₂ and 80₃.

[0038] Current I₁ exiting winding 36₂ enters winding 36₃ via one of the plated vias 86 adjacent the upper edges of layers 80₂ and 80₃. Current I₁ flows in winding 36₃ in a counterclockwise direction thereby producing a magnetic field having a polarization vector which extends outward from the patterned surface of layer 80₃.

[0039] With reference to Fig. 4b, and with ongoing reference to Figs. 2-4a, current I₁ exits winding 36₃ and enters winding 36₄ via one of the plated vias 84 adjacent the centers of windings 36₃ and 36₄. Current I₁ flows in a clockwise direction in winding 36₄ thereby producing a magnetic field having a polarization vector which extends through layer 80₄ and outward from the unpatterned surface thereof. Since windings 36₃ and 36₄ are positioned coaxially and in registration when the unpatterned surfaces of layers 80₃ and 80₄ are laminated together to form a pair of layers, as shown in Fig. 2, the polarization vectors of the magnetic fields produced by windings 36₃ and 36₄ are additive. Moreover, the magnetic fields produced by windings 36₃ and 36₄ are additive with the magnetic fields produced by windings 36₁ and 36₂.

[0040] The arrangement of windings 36-46, plated through-holes 54, plated vias 84 and 86, and heat transfer vias 62, and the arrangement of layers 80₁-80₄ discussed above, is repeated as necessary for layers (not shown) between layers 80₄-80_{x-1}. To this end, the number of layers 80 utilized to form substrate 34 is a compromise among factors, such as the width of gap 16 of stator 4, the number of ampere-turns desired of each coil 36-46, and the like.

[0041] Continuing now with the description of the illustrated embodiment, current I₁ flows through windings 36 of any layers 80 between layers 80₄ and 80_{x-1} in a manner similar to that disclosed above for layers 80₁-80₄. Referring to Fig. 5a, eventually, current I₁ enters coil 36_{x-1} via one of the plated vias 86 and flows in a counterclockwise direction in winding 36_{x-1} until it exits winding 36_{x-1} and enters winding 36_x, shown in Fig. 5b, via one of the plated vias 84 adjacent the centers of winding 36_{x-1} and 36_x. Current I₁ flowing counterclockwise in winding 36_{x-1} produces a magnetic field having a polarization vector which extends outward from the patterned surface of layer 80_{x-1}. Current I₁ flows in a clockwise direction in winding 36_x thereby producing a magnetic field having a polarization vector which extends through and outward from the unpatterned surface of layer 80_x. With layers 80_{x-1} and 80_x laminated together, as shown in Fig. 2, the polarization vectors of the magnetic fields produced by windings 36_{x-1} and 36_x in response to current I₁ flowing therethrough are in the same direction. Moreover, the magnetic fields produced in response to current I₁ flowing through windings 36_{x-1} and 36_x are additive with the magnetic fields produced by windings 36₁-36₄ discussed above.

[0042] In contrast to current I₁ exiting windings 36₁-36_{x-1}, current I₁ exits winding 36_x via a printed circuit lead 90 which extends between one of plated vias 86 associated with winding 36_x and one of the plated vias 94 associated with winding 42_x. To avoid current I₁ from returning to any of the windings 36₁-36_{x-1}, the plated vias 86 connected to printed circuit lead 90 is not directly connected to windings 36₁-36_{x-1}.

[0043] The plated via 94 connected to printed circuit lead 90 is connected in series between winding 36_x on layer 80_x and winding 42₁ on layer 80₁. Thus, current I₁ exiting winding 36_x on layer 80_x flows through printed circuit lead 90 and enters coil 42₁ on layer 80₁ via the plated via 96 connected to printed circuit lead 90.

[0044] Current I₁ flows in a counterclockwise direction in winding 42₁ until it exits winding 42₁ and enters winding 42₂ via one of the plated vias 94 adjacent the centers of windings 42₁ and 42₂. Current I₁ flows through winding 42₂ in a clockwise direction until it exits winding

42₂ and enters winding 42₃ via one of the plated vias 96 adjacent the upper edges of layers 80₂ and 80₃. Current I₁ flows in winding 42₃ in a counterclockwise direction until it exits winding 42₃ and enters winding 42₄ via one of the plated vias 94 adjacent the centers of windings 42₃ and 42₄. Current I₁ flows in winding 42₄ in a clockwise direction until it exits winding 42₄ via one of the plated vias 96.

[0045] Current I₁ flows serially through windings 42 on layers 80 between layers 80₄ and 80_{x-1} in alternating counterclockwise and clockwise directions in a manner described above for windings 42₁-42₄. Eventually, current I₁ enters winding 42_{x-1} via one of the plated vias 96 and flows in a counterclockwise direction in winding 42_{x-1} until it exits winding 42_{x-1} and enters winding 42_x via one of the plated vias 94 at the center of windings 42_{x-1}-42_x. Current I₁ flows in a clockwise direction in winding 42_x until it exits winding 42_x and flows to one of the plated through-holes 54 via a printed circuit lead 100.

[0046] As shown in Fig. 5b, the end of printed circuit lead 100 opposite the plated through hole 54 connected thereto is connected to one of the plated vias 96. To avoid current I₁ from returning to any of windings 42₁-42_{x-1}, the plated via 96 connected to printed circuit lead 100 is not directly connected to windings 42₁-42_x. It can be seen in Figs. 3a and 5b that current I₁ enters winding 36₁ via one of the plated through-holes 54 and returns to amplifier 58 via an adjacent plated through hole 54 after flowing serially through windings 36₁-36_x and 42₁-42_x.

[0047] In the illustrated embodiment, the alternating counterclockwise and clockwise winding directions of windings 38₁-38_x and 40₁-40_x, and 44₁-44_x and 46₁-46_x are the same as the counterclockwise and clockwise winding directions of windings 36₁-36_x and 42₁-42_x, respectively. More specifically, windings 38₁-38_x are connected in series with windings 44₁-44_x and windings 40₁-40_x are connected in series with windings 46₁-46_x in a manner similar to windings 36₁-36_x connected in series with windings 42₁-42_x in the manner described above. Thus, a current I₂ flows serially through windings 38₁-38_x and 44₁-44_x in the same manner described above for current I₁ flowing serially through windings 36₁-36_x and 42₁-42_x, and a current I₃ flows serially through windings 40₁-40_x and 46₁-46_x in the same manner described above for current I₁ flowing serially through windings 36₁-36_x and 42₁-42_x.

[0048] As discussed above, windings 36₁-36_x are positioned coaxially and in registration when layers 80₁-80_x are laminated together. The winding directions and interconnections of windings 36₁-36_x to each other form coil 36. Because of the interconnections and the clockwise

and counterclockwise winding directions of the windings associated with coil 36, the magnetic fields produced by windings 36_1 - 36_x have polarization vectors that extend in the same direction.

Thus, the total magnetic field produced by coil 36 is the sum of the magnetic fields produced by each winding 36_1 - 36_x thereof in response to current I_1 flowing therethrough. Similar comments apply in respect of the magnetic fields produced by current I_1 flowing through windings 42_1 - 42_x which form coil 42; current I_2 flowing through windings 38_1 - 38_x and 44_1 - 44_x which form coils 38 and 44, respectively; and current I_3 flowing through windings 40_1 - 40_x and 46_1 - 46_x which form coils 40 and 46, respectively. Since the polarization vectors of the magnetic fields produced by the windings, e.g., 36_1 - 36_x , of each coil, e.g., coil 36, extend in the same direction, the number of ampere-turns of each coil 36-46 is the sum of the ampere-turns of the windings forming each coil 36-46.

[0049] In operation of linear motor 2, amplifier 58 selectively controls a direction and duration of current I_1 through coils 36 and 42; a direction and duration of current I_2 flowing in coils 38 and 44; and a direction and duration of current I_3 flowing in coils 40 and 46 in a manner known in the art to produce on armature 8 a force which causes armature 8 to move in a desired direction along the length of gap 16.

[0050] From the foregoing description, it should be appreciated that armature 8 is configured for a three-phase electrical operation, with coils 36 and 42 connected to a first electrical phase of amplifier 58, coils 38 and 44 connected to a second electrical phase of amplifier 58, and with coils 40 and 46 connected to the third electrical phase of amplifier 58. Depending on the application of linear motor 2, however, armature 8 can be configured to receive more or less electrical phases from amplifier 58. In addition, armature 8 can be configured to have more or less than two coils per electrical phase, with the number of coils per electrical phase being determined by the amount of force to be generated by forcer 6. Still further, it should be appreciated that the direction of current I in adjacent windings forming each coil flows in the same direction. Thus, the force produced by current I flowing through the windings of each coil 36-46 in the presence of a magnetic field produced thereacross by magnet assembly 20 are additive. Lastly, the number of layers 80 that are laminated together to form armature 8 can be selected as a compromise between the desired ampere-turn of each coil 36-46, the maximum current I each coil 36-46 is configured to receive, and the maximum force to be produced by armature 8.

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[0051] With reference back to Fig. 2, to facilitate transfer of heat from inner layers of layers 80 of armature 8, insulating spacers 102, shown in phantom in Fig. 2, can be received between two or more layers 80 forming substrate 34. Support pins/brackets 104, shown in phantom, can be utilized to secure the opposing surfaces of two layers 80 in opposition with spacers 102 sandwiched therebetween. Plural conductive wires 106, shown in phantom, can extend between the plated through-holes 54 and the plated vias, e.g., 84, 86, 94 and 96, extending between the windings of each coil 36-46, to form interconnections between the windings of each coil 36-46 held in opposition by spacers 102. Preferably, each pair of layers 80 having their patterned surfaces facing each other are spaced in opposition by spacers 102. If, however, the width of gap 16 will not permit spacers 102 between each pair of opposing patterned surfaces of layers 80₁-80_x, one or more sets of spacers 102 can be selectively positioned between two or more layers 80 of armature 8. Spacers 102 can be utilized with or without heat transfer vias 62.

[0052] The invention has been described with reference to the preferred embodiments. Obvious modifications and alterations will occur to others upon reading and understanding the preceding detailed description. For example, while described in connection with a U-shaped magnet track 12, the magnet track could be a linear magnet track and substrate 34 could be held in spaced parallel relation with the magnets of such linear magnet track by suitable fixturing known in the art. Moreover, windings can be included on both surfaces of one or more of the layers 80 forming substrate 34. Still further, the alternating clockwise and counterclockwise winding directions of the windings forming each coil can be avoided by forming each coil with windings having the same winding direction and laminating the layers 80 together with their respective patterned surfaces facing the same direction. Moreover, while each layer 80 is described as having windings, e.g., 42₁-42_x, configured to be connected to two or more phases of amplifier 58, each layer 80 can include windings configured to be connected to only one phase of amplifier 58. More specifically, two or more layers 80 can be laminated together to form a group of layers 80 having its windings electrically connected to one phase of amplifier 58. Plural groups of layers 80 can be formed and positioned adjacent each other with each group connected to a different phase of amplifier 58. Lastly, while the preferred embodiments are described as having the windings and coils of each phase connected in series, the windings and coils of each phase can be connected in parallel, or in some combination of series and parallel. It is intended

that the invention be construed as including all such modifications and alterations insofar as they come within the scope of appended claims or the equivalents thereof.

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